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Some Aspects of Submarine Design **Part 2. Shape of a Submarine 2026**

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ABSTRACT

A shape for a next generation submarine has been drawn based on a survey of available knowledge. The reasons for each detailed portion of the shape are explained. The aim of the design is to produce a submarine with minimum practical resistance and with minimum water flow noise especially over the forward passive sonar while still carrying out all its normal functions.

It is assumed the role of the submarine would be little different from the current vessel but may be powered differently and carry different equipment.

The diameter of the hull has been increased while the length has been decreased compared to the present vessel. It is estimated the comparative resistance will be reduced by ten percent. The larger diameter will allow an extra deck over a portion of the length of the vessel giving greater flexibility to internal arrangements. All openings in the first five metres of the shape have been moved elsewhere including the torpedo tubes and interceptor array, to give the smoothest possible flow over the forward passive sensors.

The nose shape is derived from a NACA forebody with a 14.2 percent thickness-length ratio and shows a favourable value of the minimum pressure over its length. The question of achieving natural laminar flow over this short length is discussed and found to be possible but is unproven.

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EXECUTIVE SUMMARY

In about the year 2026, the present class of Australian submarines, the Collins class, will be approaching obsolescence. The machinery, the structure, communications, sensors, weaponry will need updating and replacing and the hull structure will have reached the end of its design life. This represents an opportunity to improve certain aspects of the design which is only possible with a new vessel.

One of the most important aspects of submarine operation is to move as silently as possible and to be able to detect others with passive sonar. Consequently this exercise in developing the shape of a new design has three aims, 1) to move as silently as possible with the lowest practical resistance, thus giving a greater top speed and less fuel consumption at transit speeds, 2) to give the best possible flow over the forward passive sonar and 3) a more flexible interior volume with more deck space. All this should be possible without in any way compromising all the other functions and operations.

A shape is shown with the best practical ratio of length-to-diameter which gives the minimum resistance. The diameter has been increased while the length has been decreased compared to Collins. The increase in diameter allows an extra deck over portion of the length of the vessel but should not increase the draft to a limit which would interfere with navigation in ports or when docking. It will add to the minimum depth for dived operations where a mission justifies risking the submarine. It will also add to the minimum operational depth of water which enables a submarine to duck under a ship. In order to maintain the same diving depth as Collins, the frames need to be stronger. This should be accomplished by deeper webs.

A mathematically derived nose shape has been drawn which maintains perfect symmetry over the first five meters from the nose. This shape should give the planned pressure distribution and properly constructed to the finest tolerances, will probably give laminar flow in this region. The passive sonar would then have superior capabilities. The problems with maintaining laminar flow are discussed and it does appear feasible. In the event the boundary layer is tripped to turbulence the result will still represent a vast improvement over the present nose shape and flow over the sonar.

The construction of the pressure hull follows standard practice, with successive truncated cones forming part of the forebody and all the afterbody. A length of parallel mid-body joins the nose and tail. The casing is not formed until aft of station 5000 (5 metres) and the distortion from circular is gradual thus preserving the symmetry of the nose ahead. The casing is blended into the circular hull smoothly without longitudinal valleys. The torpedo tubes have been moved aft from a horizontal line across the nose to two vertical lines on either side with the most forward part of the shutter at station 5000. The turtle back has been shaped in an attempt to minimise lateral pressure variation.

Model testing is essential to confirm design changes and to establish measured values for speed-power relationships. It is estimated for equal volumes the total resistance would be reduced by ten percent compared to a shape like Collins.

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P.N Joubert, a World War II fighter pilot, after demobilisation from the RAAF, studied aeronautical engineering at Sydney University. He then joined CSIRO, where he designed a radio controlled meteorological glider. Subsequently he was appointed as a lecturer in mechanical engineering at Melbourne University specialising in fluid mechanics. In 1954 he attended the MIT where he built and tested high-speed catamarans in the towing tank. At Melbourne University he built a new wind tunnel and much research was initiated and conducted there. He has authored over 120 scientific papers, most of them in fluid mechanics, boundary layers, roughness, and vortices and recently with a PhD student, the flow about a submarine body in a turn. Over the years he has received many research grants including one from the US Navy. His work with his students and colleagues is recognised internationally such as by the General Motors Research Laboratories and other international ship research bodies. He has been studying flow patterns on submersibles since 1998 and has helped with certain modifications to Collins. In 1972 he was granted a personal chair and since retirement has been invited to continue as a Professorial Fellow. He was awarded a medal in the Order of Australia in 1996 for contributions to road and yacht safety. He was awarded the AGM Michell medal in 2001 by the College of Mechanical Engineers and is a Fellow of the Australian Academy of Technological Science and Engineering. In 2005 he was awarded an honorary Doctorate of Engineering by the University of Melbourne for his distinguished eminence. As a yacht designer he has had over 100 yachts built to his designs, including a high-speed catamaran for the world sailing speed record and ocean racing yachts. Some of these have won against world-class competition, the Sydney-to-Hobart race in 1983 and second places in 1968, 2002 and 2003. As a sailor he has raced his own designs in 27 Sydney-to-Hobart races and survived the storm of 1998. In 1993 he was awarded the Commodore's medal of the Cruising Yacht Club of Australia for outstanding seamanship after his crew had rescued eight survivors from a sunken yacht at night in a strong gale.

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Glossary

AIP Air Independent Propulsion

CSIRO Commonwealth Scientific and Industrial Research Organisation

MPD Maritime Platforms Division

NACA National Advisory Council of Aeronautics (forerunner to NASA)

NASA National Aeronautical and Space Administration

RAAF Royal Australian Air Force

SSPA Swedish Maritime Research Laboratory

μ Fluid viscosity

ρ Fluid density

A Surface area

D Body diameter

F_f Friction force

L Body length

U_∞ Freestream fluid velocity

Re Reynolds number, a ratio of fluid inertial and viscous forces, $= \frac{\rho U_\infty L}{\mu}$

Re_x Local value of Reynolds number, usually measured at transition point

C_p Pressure Coefficient $= \frac{\text{Pressure}}{\frac{1}{2}\rho U_\infty^2}$

C_f Skin-friction Coefficient $= \frac{F_f}{\frac{1}{2}\rho U_\infty^2 A}$

C_P Prismatic Coefficient $= \frac{\text{Displaced Volume}}{\text{Midship Area} \times \text{Waterline Length}}$

t Sail thickness

c Sail chord (length)

1 Introduction

Considering a replacement design for the Collins Class Submarine which might be required about the year 2026, at this time of writing, the operational tasks required of this submarine would not appear to be greatly different to what was listed in the report of December 2003, [1]. If the tasks are altered then of course the design will need to be altered.

What is discussed here is preliminary; it is intended that it may form a basis for what eventually is decided.

It is highly likely the range requirements would be at least as large as Collins (10,000 nautical miles) and probably extended given the expanded area of interest flagged in the Minister's Defence update 15 December 2005.

It would be highly desirable if the transit speed could be increased to minimise time lost in transit.

The type of power unit must be left to later developments. AIP may have possibilities. Nuclear power would allow a fast transit but is not yet acceptable in Australia.

Diving depth is a most important variable and some designs have gone to much trouble and expense in order to achieve the deepest possible operating depth. Whether this feature needs to be altered I cannot say, but it will be assumed that there is no change required. In which case the pressure hull can be ended with flat bulkheads as with Collins Class. A deeper diving depth would require domed end closures which present greater difficulties to construct (Daniel [3]). The whole submarine then becomes more expensive. The greater depth would require a stronger hull and as a result the hull weight would be increased leaving less available for fuel, machinery and other items. This in turn means a slower vessel. One makes a design choice and suffers the consequences.

Weaponry is being altered on a continuous basis. Launch systems which allow the use of stand-off land attack missiles, surface to air missiles and anti-ship missiles will probably need to be considered and included.

The ability to carry and launch unmanned underwater vehicles will be part of the wish list as will likely be the operational support of special operations forces.

Detection and communications are being improved constantly. Covert forward intelligence gathering and surveillance is an important activity and it is equally important to be able to communicate this information. The ability to communicate real time data with voice transfer would surely be an aim. Sloan [2] discusses some of these factors from the designers viewpoint. At some stage decisions are made, the design is commenced and thereafter the process becomes difficult to alter in any major way.

The aim of this design study is to produce a shape with the following features,

1. Minimum resistance within all other design constraints, thus increasing cruising range, top speed and reducing fuel consumption.
2. Minimum flow noise especially over the forward sonar and other sensors.
3. A flexible interior giving most deck space for a given volume.

2 Criteria for Optimum Shape of a Submarine

Gertler, in 1950 [10], reported the results of resistance experiments on a systematic series of twenty four mathematically related streamlined bodies of revolution, showing how the resistance of these bodies at deep submergence varies with changes in five selected geometrical parameters. These geometrical parameters were the fineness ratio, prismatic coefficient, nose radius, tail radius and the position of the maximum section. Before this work was undertaken there was no systematic data on the resistance of streamlined forms deeply submerged in a fluid.

The series forms were compared on an equal volume basis including the estimated added resistance due to control surfaces necessary for prescribed directional stability characteristics. These comparisons indicated that there is a large variation in submerged resistance among these forms and that there is a definite minimum resistance on each parameter variation except for the nose radius.

These test results formed the basis for the choice of the shape of the USS Albacore [25], whose construction was authorised in 1951. This experimental vessel was the forerunner of all successful US Navy submarines such as Barbel and Skipjack.

2.1 Cross-Section

To withstand the high pressures on the hull at depth, the most efficient structural shape with the lowest stresses is one of circular cross-section.

Departures from absolute circularity have to be minimised as discussed by Capt. H. E. Saunders [4], otherwise early failures can result (see Appendix A). The circle has the lowest wetted surface for a given contained volume so this is an advantage for underwater resistance.

For surface travel the circle contributes no hull form stability which is a disadvantage especially when a vessel rises to the surface with water in the voids of the sail and casing thus momentarily increasing the height of the centre of mass and decreasing the stability margin.

2.2 Length-to-Diameter Ratio

The ratio of length-to-diameter bears a strong effect on the total resistance. The two main portions of the underwater resistance of the bare hull are due to pressure drag (sometimes called form drag) and skin friction.

The pressure drag is created by the streamlines on the rear of the body being displaced from the geometric surface by the thickening boundary layer. Consequently the rise in pressure near the tail of the body as the streamlines widen, is not as great as would occur without a boundary layer. This imbalance between nose and tail produces a nett pressure force on the submarine creating a drag force.

Skin friction drag acts tangentially at the surface and is proportional to the wetted surface. The more wetted surface the greater the skin friction. Therefore if the displaced

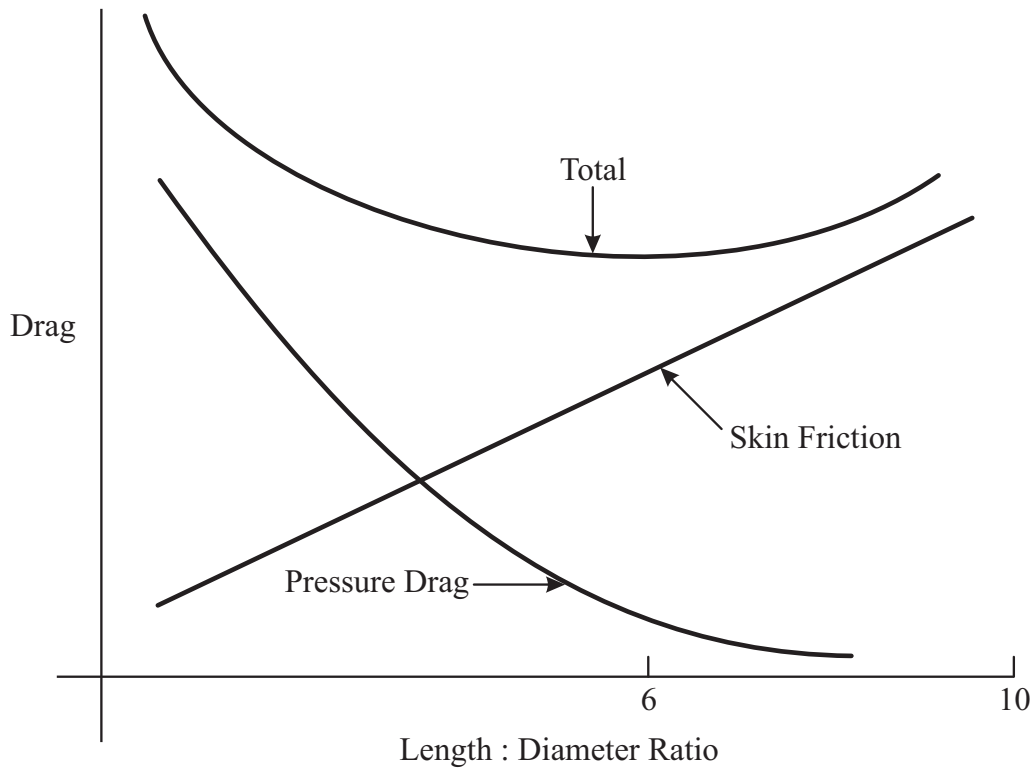


Figure 1: Drag components for constant volume form.

volume of the submarine is contained in a long thin shape, then the skin friction is greater than for a shorter, beamier shape of the same volume which has less wetted surface.

The variation in the two components of resistance, pressure drag and skin friction, looks like the plot in Figure 1.

The combined resistance shows a minimum at about L/D of 6 to 7; the curve has no defined minimum being almost horizontal in this range.

It is proposed that a new shape be considered of shorter length and greater diameter which will reduce the total drag coefficient closer to the ideal.

2.3 Surface Roughness

The main factor, apart from surface area, which affects the skin friction resistance is the roughness of the surface. It is important that designers limit the effects of surface openings, raised edges, recessed joints (shutters), lateral arrays and other features which cause added resistance.

2.4 Prismatic Coefficient

The prismatic coefficient defines the amount of volume in the ends of the submarine. It is formed as the ratio of the displaced volume with that contained in a prism formed by the

mid-ship cross-sectional area and the length. The variation of the submerged resistance with this parameter can be significant (see Figure 10 in Gertler [10]). R. J. Daniel in his paper on submarine design [3] suggests an optimum value of about 0.6 (also shown in Gertler).

Collins has a prismatic coefficient greater than 0.8, while the new shape for 2026 calculates as 0.76.

The variation of the resistance with change in prismatic is shown by Arentzen and Mandel [6] in their Figure 6. Figure 2 shows this variation.

The combined effect of the reduction in L/D and C_P should give a reduction in total resistance coefficient of over eight percent.

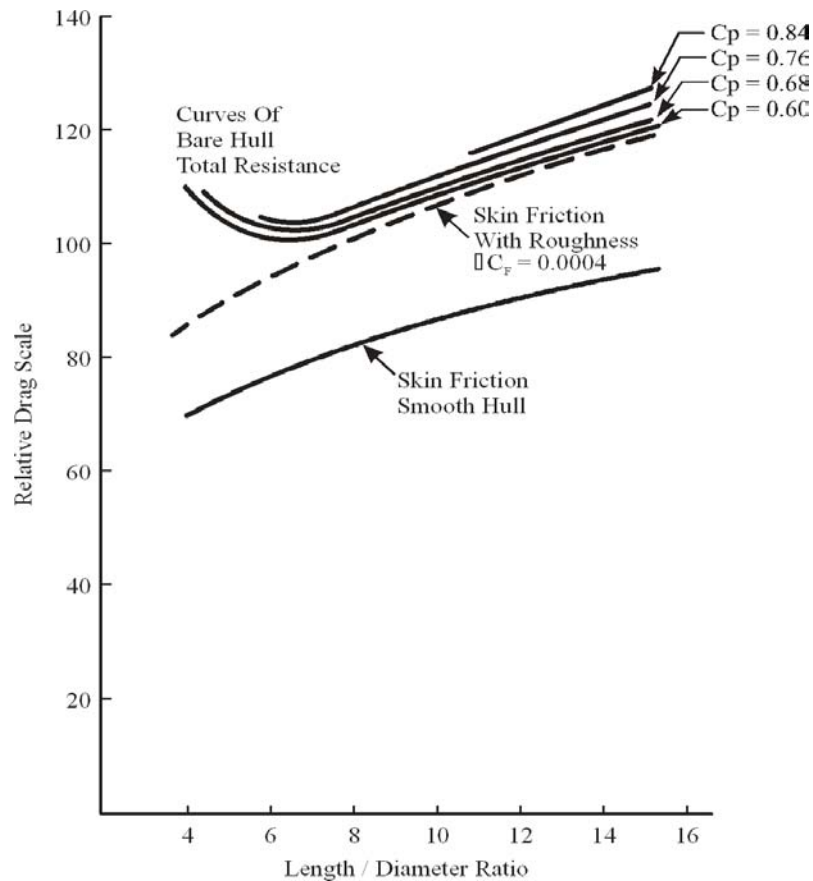


Figure 2: Total resistance components for bare hull showing effect of change in prismatic coefficient (Arentzen and Mandel [6]).

2.5 Limitations on Draft

It should be possible to increase the floating draft of a submarine to greater than that of Collins, which is nominally 7.0 metres, and still be able to navigate the important harbours where it docks and berths.

The weight of any new vessel needs to be established early in the design. Hence the floating draft can be established from the displaced volume required to support this weight added to all the other loadings. Arentzen and Mandel [6] suggest that 36 feet (10.98 metres) is the upper practical limit for the diameter of a military submarine which would have a draft of 30 feet (9.14 metres).

Of more importance is the operational requirement of a dived intrusion in shallow water where the submarine may be at risk. The bottom clearance plus the hull diameter with the casing height plus the fin and periscope heights are now increased by the larger hull diameter.

A similar increase affects the minimum depth of water to enable a submarine to duck under a deep draft ship.

With the new shape a minimum increase in diameter is suggested which involves the least increase in weight of the construction but provides more usable deck space.

2.6 Diving Depth (Critical Pressure)

Timoshenko [5, pp186-188] discusses the buckling of reinforcing rings for submarines and shows that the second moment of area formed by the cross-section of the ring, which may include part of the skin, needs to be maintained in the same ratio with the cube of the diameter in order to maintain the same critical collapse pressure. To reach the same diving depth with the same factor of safety as Collins, the larger diameter vessel will need stronger rings with deeper webs. This is a penalty for increasing the diameter.

2.7 Number of Decks

An important consequence of an increase in diameter involves the number of decks.

Collins with diameter of 7.8 m contains three decks. The floor-to-floor height of the 'tween-decks is about 2.15 m. It is quite possible to have two tween decks with this headroom and almost the same headroom as Collins for the upper and lowest decks. The hull diameter then becomes 9.6 m.

Arentzen and Mandel [6] on p. 636, Figure 12, show four levels with hull diameters ranging from 31 to 36 feet (see Figure 3). The proposed diameter of 9.6 m or 31.5 feet fits in this range.

Figure 4 (Daniel, [3]) shows the range of diameters for four decks as 10-11 m which is a little greater than the US preference.

Four decks give greater flexibility of arrangements within a given volume and Arentzen and Mandel suggest deck area per unit volume is a desirable criteria. Their Figure 13 shows

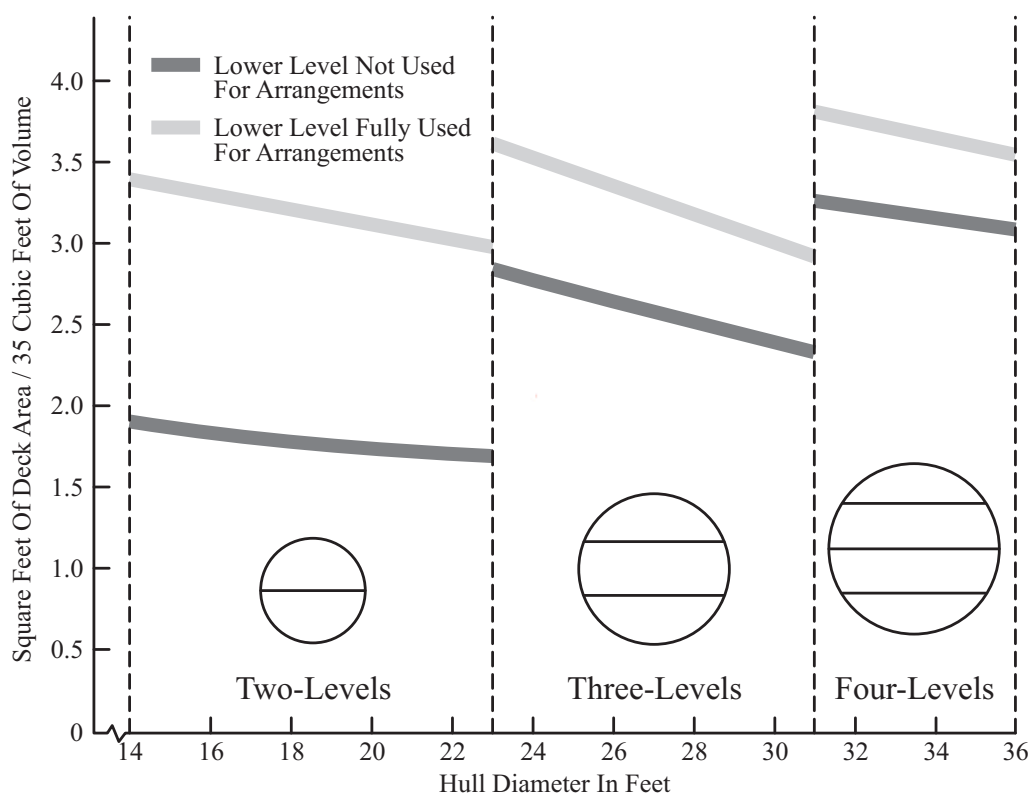


Figure 3: Number of decks with hull diameter. Also useful deck area (Arentzen and Mandel [6]).

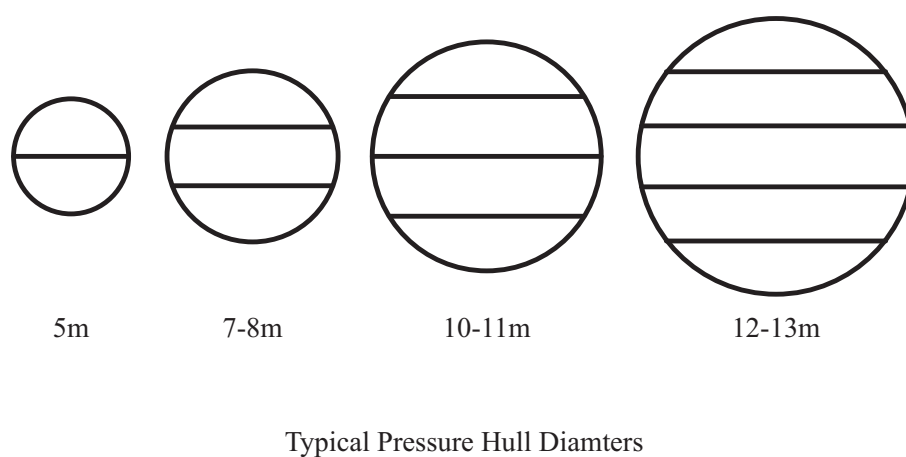


Figure 4: Number of decks with hull diameter (Daniel [3]).

examples of effective deck area. They comment, “There is no gain by having the diameter larger than the minimum.”

3 Length of 2026

After examining the profile of a vessel with $L/D = 6.0$, when length L is $6 \times 9.6 = 57.6$ m, this appears too short to fit the items of machinery and power found in Collins. Many of these items are of such density, they need to be placed as low as possible.

The batteries are a priority item for placing on the lowest deck. All these features have to be arranged by the designer in the jigsaw puzzle to create a workable design. At this stage it is not possible to say what size the batteries may be as they are subject to improvements.

On first glance the length needs to be larger than 58 m.

A length of 70 m would appear to accommodate all that is needed so try this as a first step. The L/D is then 7.3 which is just outside the desired range (L/D of Albacore was 7.723).

It is easy enough to adjust the length on the drawing board by merely altering the length of the parallel mid-section.

Until the type of power is decided, as well as the weaponry and other major factors, the length is a variable which can be adjusted to fit all that is required.

4 Flow Over the Nose

A major aim in this design study is to shape a nose which gives all the desirable qualities. It is most important that the flow around the nose housing the bow sonar be as ideal as possible. This forward sonar must be able to receive signals while the vessel is moving at speed, not just when it is stationary.

Flow noise has to be kept to a minimum, if possible, with a laminar boundary layer, but certainly with no additional noise if the boundary layer is turbulent.

Admiral Hervey [8, pp 93-94], comments, when discussing passive sonar reception, “Difficulties increase steeply when submarines have to act in the defensive sea control, escort role. To maintain station on a surface group, they must travel at speeds well over 20 knots and ideally need a top sonar operating speed which matches their speed through the water. This aim can only be achieved by very good array designs and *maybe reconfiguring the whole bow to reduce water flow noise*. This may seem an extreme measure but a severe penalty has to be paid for leaving the difficulty unresolved.”

While Australian submarines currently transit at lower speeds, this is still a problem.

Research conducted by the Swedish Maritime Research Laboratory SSPA [7], shows how a nose shape with a highly curved forehead immediately over the forward sonar, can

produce cavitation when at speed. Cavitation would overwhelm any incoming signal to the passive sonar.

Loid and Byström, researchers at SSPA [7], remark,

“There are heavy demands on the acoustic search system so that the submarine can serve in an optimal way. Because of its non-disclosing character, the passive hydrophone is the most important information system of the submarine.”

Further on they say, “Laminar flow conditions cannot be maintained in the area of the hydrophone location, not even at low speeds, as the flow is disturbed by torpedo tube hatches and irregularities.”

They conclude by saying, “it is important that the hull design leads to low and uniformly distributed local velocities along and in the vicinity of the hydrophone window. Further, the local velocity should be a strictly monotone function with a value increasing up to and abaft the hydrophone.”

They have presented an argument with but one answer; the nose should be properly shaped and all openings, even though shuttered, should be placed elsewhere. The torpedo tubes *should not* exit through the nose.

E. S. Krauss, a researcher from the British Aircraft Corporation, discussed the effect on drag of bluntness of the noses on bodies of revolution [17]. For the flow conditions of a fully turbulent boundary layer with the aspect-ratio of the elliptic nose shape of a body of revolution within acceptable limits of bluntness, while the body is subject to an increase in Reynolds number, the friction drag coefficient varies in the same way as does the drag coefficient for a flat plate. Then it will reduce from about $C_f = 0.005$ at $Re = 10^6$ to $C_f = 0.002$ at $Re = 3 \times 10^8$ (plus any added effects due to roughness).

However if the nose is too blunt and the associated local adverse pressure gradient is too great, then the skin-friction coefficient no longer reduces with increase in Re (as the submarine goes faster) but indeed it remains constant at the higher value. Thus it appears possible for a blunt nosed body of revolution to operate at over twice the resistance of one with a properly shaped nose. Whether this result applies to a shape like Collins needs consideration.

4.1 Torpedo Tubes

The shutters covering the exit holes in the nose never fit perfectly. They then act as a source of transition for a laminar boundary layer and an added roughness factor should the boundary layer already be turbulent. They are also a source of additional noise affecting the performance of the forward sonar.

The tubes in the new design have been moved aft to positions similar to those on many US submarines. They are arranged in two vertical banks of three tubes on either side. The most forward point of an opening to a shutter should then be aft of the point which could affect the performance of the forward sonar (see Section 4.4). This requires the forward edge of the shutter to be at say, station 5000.

To achieve this, the forward bulkhead could be moved aft from its position in Collins (station 7590) to say station 9000, a distance of 1.410 metres. This change again illustrates

the problem of design. Change one feature for a perceived advantage and there are changes required throughout the whole jigsaw puzzle.

A better alternative to moving the bulkhead, which involves loss of internal volume, is the arrangement shown in Figure 9. The pressure hull is reduced by a conical section forward of station 10,000. Once the torpedo is clear a constant section is resumed forward to a station clear of the passive sonar.

The torpedo tubes and the torpedoes are of such density, their vertical position has an effect on the stability margin so it is desirable they be placed as low as possible. A reduction in the number of tubes to four would aid in this regard. Four only tubes were tried by the US Navy but left the submarine defenceless under certain operational conditions. Recent US submarines have more tubes.

4.2 Intercept Array

The location of the intercept array needs to be carefully considered. Such an array elevated above the surface of the submarine on a non-streamlined pedestal, would not only carry a horseshoe vortex about the base of the pedestal but would create large separated wake vortices behind its non-streamlined shape. It would create much noise. Such an arrangement placed contiguously with the forward sonar would not be a wise position.

Alternatively the photograph in Figure 8.24 of a British submarine shows the intercept array positioned above deck, forward of the sail, but well aft of the nose (shown here as Figure 5). Progress with new designs of arrays should allow non-obstructive detection methods.

4.3 Natural Laminar Boundary Layers at High Reynolds Number

Apart from having much lower skin friction resistance, laminar boundary layers are much quieter than a turbulent boundary layer especially for noise transmitted through the surface of the vessel to an internally positioned sensor.

It would be highly desirable if a natural laminar boundary layer could be maintained over the critical part of the nose up to the service speeds; the higher the better.

There has been quite an effort over the last century to reduce the drag of large submerged vehicles such as airships and submarines, by shaping them to proven physical principles. This can lead to unusual shapes which are impractical for submarines.

Carmichael [11] tested streamlined torpedo shapes in drop tests in the Pacific Ocean. One shape, the ‘Dolphin’, had half the drag of a conventional torpedo due to a long run of laminar boundary layer. Transition occurred at a Reynolds number of $Re_x = 1.84 \times 10^7$.

The transition point was located aft of the point of maximum thickness of the body as shown in Figure 6.



Figure 5: Externally positioned intercept array (Hervey [8]).

Parsons, Goodson and Goldschmied [12] claim, that by exploiting laminar flow while avoiding turbulent separation, a body with a drag coefficient one third below the best existing laminar design has been obtained. Their shape is also shown in Figure 6.

Contrary to the above, John L. Hess in his study [13], comments that, “Operational speeds for undersea vehicles are large enough so that maintaining any significant portion of the boundary layer as laminar is extremely difficult at best and probably impossible under real operating conditions. In particular a degree of surface perfection is required that could never be maintained in continuous service.”

Gertler [10] discounted any laminar flow effects in his study and assumed a fully turbulent boundary layer would apply at full scale.

After this brief survey it is clear that the only practical possibility for a naturally occurring laminar boundary layer on an operational submarine would be over the carefully shaped and precisely built nosepiece.

While the achievement of this aim would produce less frictional drag over the short length of the portion of the nose, the primary aim would be to improve the capabilities of the forward sonar.

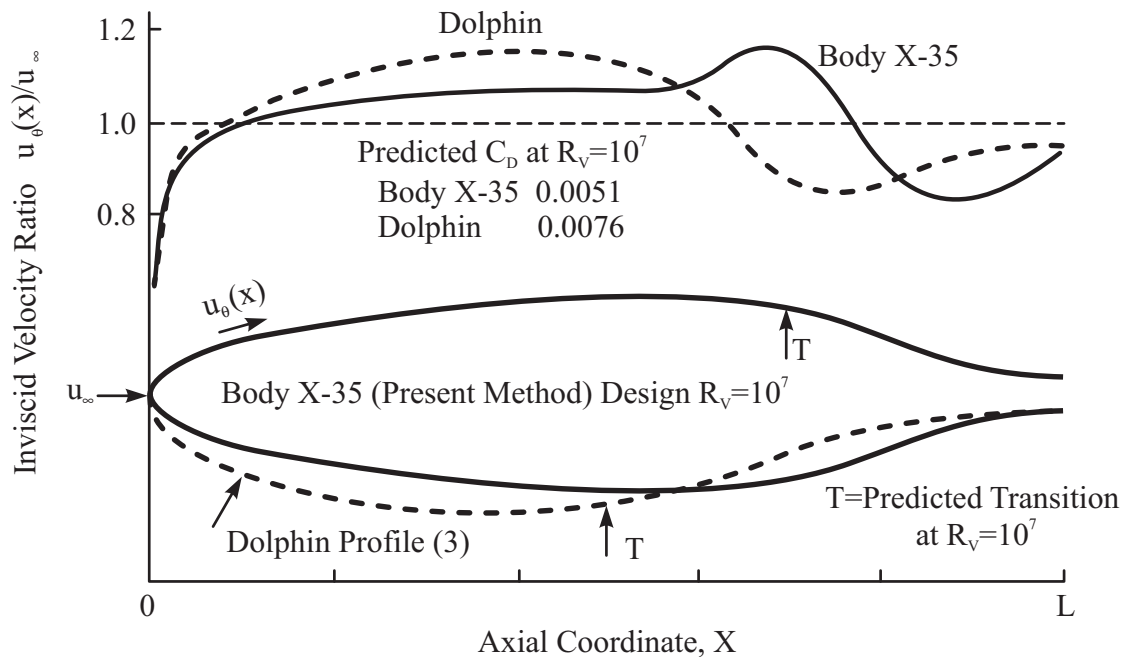
Some researchers are positive about the possibilities of maintaining a short length of natural laminar boundary layer while others are unsupportive.

4.4 Possibilities for Natural Laminar Flow

The classic text on boundary layer theory was written by Hermann Schlichting. In the fourth edition (1960) [15] in chapter XVII, he discusses boundary layer transition. Section (b) discusses the position of the point of instability for a prescribed body shape.

The discussion is summarised on p. 423 viz.

1. The theory of stability shows that the pressure gradient exerts an overwhelming influence on the stability of the laminar boundary layer; a decrease in pressure in the downstream direction has a stabilising effect, whereas increasing pressure leads to instability.
2. In consequence the position of the point of maximum velocity of the potential velocity distribution function (= point of minimum pressure) influences decisively the position of the point of instability and of the point of transition. It can be assumed, as a rough guiding rule, that at medium Reynolds numbers ($Re = 10^6$ to 10^7) the point of instability coincides with the point of minimum pressure and that the point of transition follows shortly afterwards.
3. As the angle of incidence of an aerofoil is increased at a constant Reynolds number, the points of instability and transition move forwards on the suction side and



Comparison of profiles and velocity distributions for the low-drag laminar body X-35 and the Dolphin.

Figure 6: Profiles of high speed Dolphin body and proposed X-35 showing transition points (Carmichael [11] and Parsons, Goodson and Goldschmied [12]).

rearward on the pressure side.

4. As the Reynolds number is increased at constant incidence the points of instability and transition move forward.
5. At very high Reynolds numbers and with a flat pressure minimum, the point of instability may, under certain circumstances, slightly precede the point of minimum pressure.
6. Even at low Reynolds numbers ($Re = 10^5$ to 10^6) the points of instability and transition precede the point of laminar separation; under certain circumstances the laminar boundary layer may become separated and may re-attach as a turbulent boundary layer.

Consider the flow on the nose of our new submarine to examine the possibilities for laminar flow.

A longitudinal peripheral measurement on a symmetrical nose from the forward stagnation point to a point at the aft end of the forward sonar might be 5.7 metres at about station 4000.

The Reynolds Number Re based on the total length of Collins traveling at 10 knots in standard sea water is 3.2×10^8 . This reduces to 4×10^6 per metre, again at 10 knots. The local Re_x at the arbitrarily chosen point with the distance x , measured along the curved surface 5.7 m is then,

$$\begin{aligned} Re_x &= 5.7 \times 4 \times 10^6 \\ &= 22.8 \times 10^6 \end{aligned}$$

The question is can a natural laminar boundary layer exist at this Re ?

Apart from the experiment of Carmichael there are very few reliable experimental results at these high values of Re as reported by Lutz & Wagner on p. 348 [14].

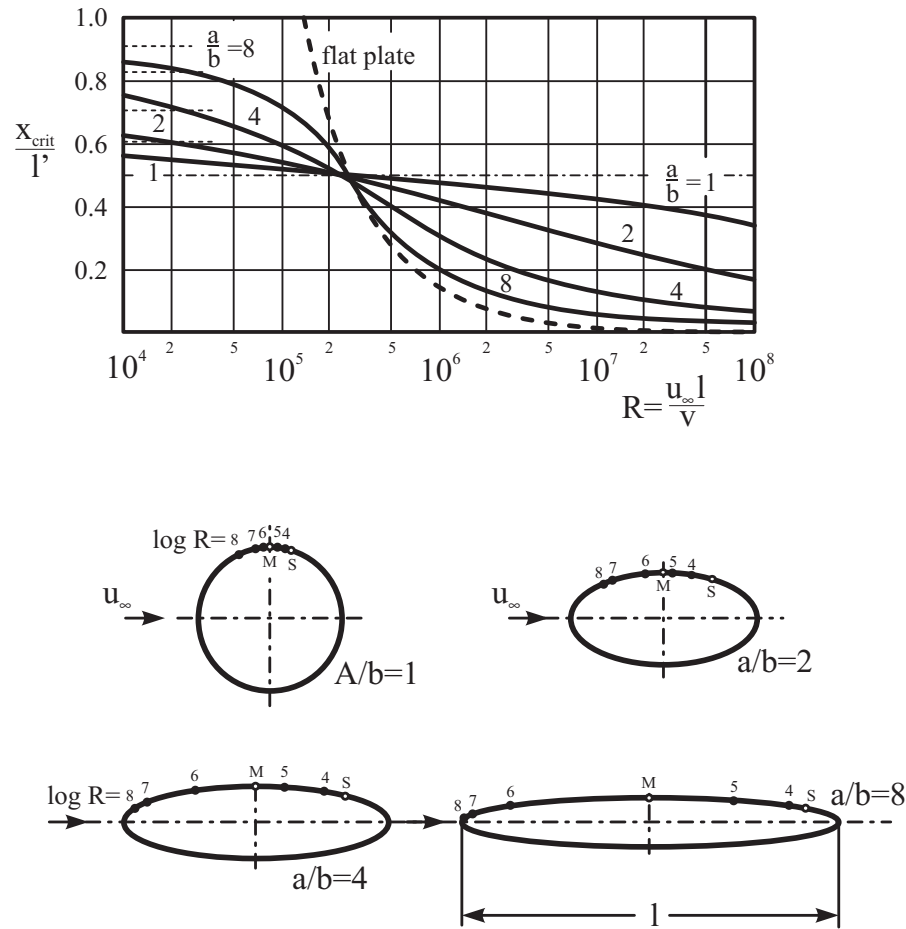
Holmes *et al* [20], found during in-flight measurements of transition points on a number of different aircraft, that the local Re of transition, Re_x was 11.1×10^6 and this occurred aft of the point of minimum pressure.

Runyan *et al* [21], found from flight tests on F-111 swept wing aircraft, natural laminar flow up to Re_x of 16.2×10^6 . This transition point occurred at 56% of chord length.

Schlichting [13] shows in his Figure 17.5 on p. 416 (repeated here as Figure 7) the critical point of instability (which precedes the point of transition) for two-dimensional elliptic cylinders of different aspect-ratios. There are no results for flow on axi-symmetric bodies. With the aspect-ratio of the nose for 2026 of 3.33, these results show that the distance to the point of instability is 4.8 metres at $Re_x = 22 \times 10^6$.

The two-dimensional flow described by Schlichting does not include the effect of lateral streamline divergence found with flow over the nose of an ellipsoid where the circumference is increasing with length from the nose up to the station of maximum cross-section.

E. S. Krauss [16] states that this effect reduces the drag on bodies of revolution (aircraft fuselages) because of increased length of laminar flow. Therefore the Schlichting results



Position of points of instability for elliptic cylinders of slenderness ratio $a/b=1,2,4,8,\infty$ (flat plate) plotted against the body Reynolds number R

$2l'$ - circumference; S - point of laminar separation; M - point of minimum pressure

Figure 7: Instability points on two-dimensional elliptic cylinders and Re (Schlichting [15]).

are not directly applicable to our submarine nose. They are only indicative of transition and appear to underpredict the value of Re_x . In other words there is a strong possibility that with an extended falling pressure gradient over the area of significance and as we will see, using the best construction techniques with no surface waviness, laminar flow becomes probable.

4.5 Prediction of Transition

Without verification by experiment the only method for finding the points of instability and transition is by analysis. There is no completely rigorous analysis available only semi-empirical methods. A comprehensive review is given by Kachanov [18].

One semi-empirical method is called the e^n criterion which is based on linear stability theory. It is quite complicated to apply and involves much work, therefore is beyond the scope of this present paper. See Lutz and Wagner [9] for an application of this method. The authors note that with the e^n method only one amplitude ratio of the disturbances waves is evaluated. The process of receptivity and the magnitude as well as the spectral distribution of the initial perturbation amplitude is not considered. The assumption of local parallelism and the neglect of non-linear effects are further simplifications of the real transition process.

How far this theory can be applied to higher Re has not been demonstrated.

Zedan *et al* [19], suggests there is no transition criteria that is reliable over a range of geometry and flow conditions. They tried four different criteria with mixed results for a low drag body where transition had been established.

4.6 Nose Shape for 2026

The paper by the Swedish researchers, Loid and Byström [7], includes a section titled, “Criteria of the Forebody Design.” They refer to the need for model testing in order to check the pressure distribution and the point of minimum pressure.

They also establish pressure distributions for different shaped forebodies by calculation and the comparative levels of boundary layer noise for the different shapes are also established. This gives the reduction in range of the respective hydrophones as the boundary layer noise increases.

They refer to the gradient of the pressure coefficient, and say it should be small with the minimum as far aft as possible. They state the obvious (which is not obvious to some designers) that the shortest forebodies have the lowest pressure minimum and a hemisphere joined to a cylinder has the lowest pressure coefficient, about -0.74 , which is a highly undesirable value.

They then show the results of their studies for twelve different forebodies.

The nose profile which best meets the stated desirable criteria of

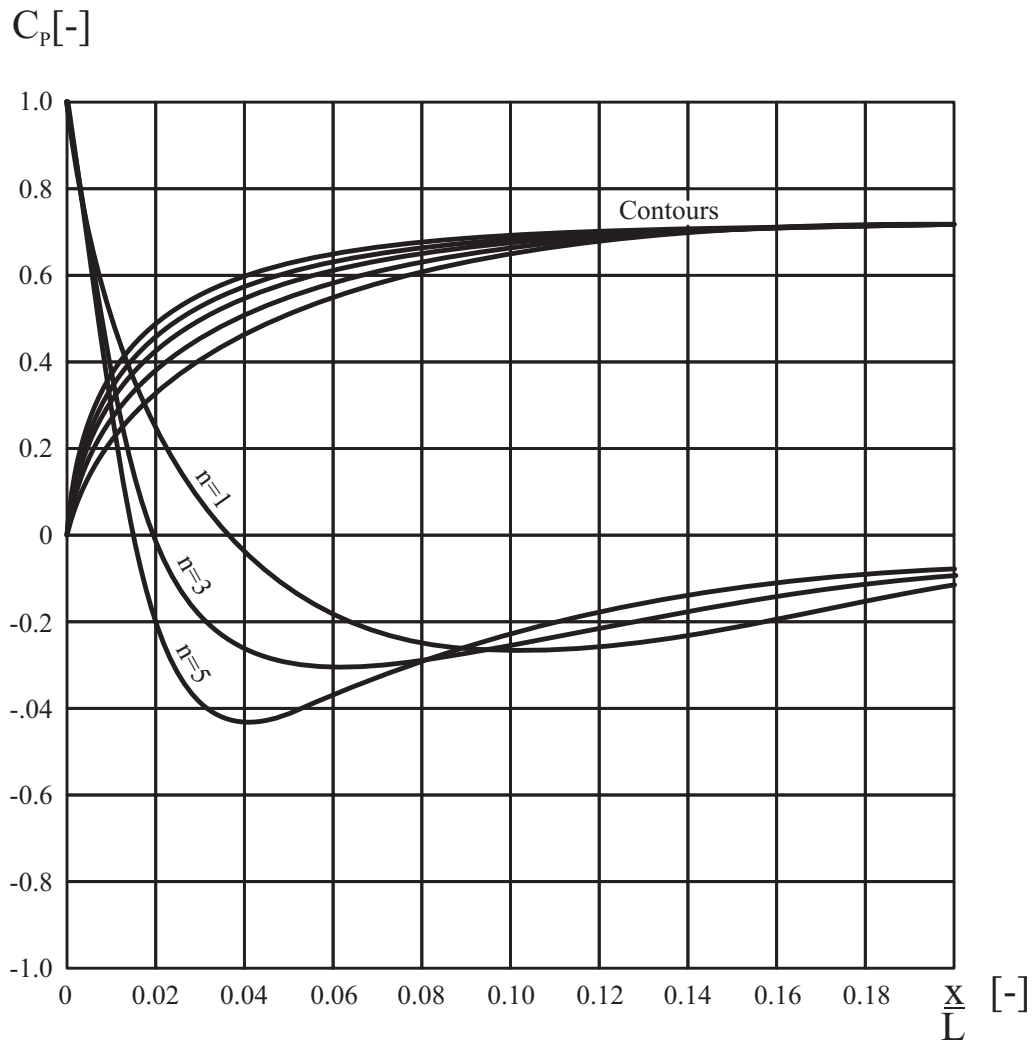
1. the smallest value of the negative pressure coefficient,
2. the smallest pressure gradient and
3. the minimum value of the pressure coefficient as far aft as possible,

was then chosen for this preliminary 2026 design study.

While it may be possible to find a better shape, at this stage, repeating the work of these knowledgeable researchers would be of no major benefit.

The profile chosen is $n = 1$ according to NACA 0014.2 - N00.20 and is shown in Figure 8.

In order to relieve the rise in pressure which occurs aft of $x/L = 0.11$ as in the above figure, the shape has been splined to extend further aft than $x/L = 0.2$. This small change will be checked for the hoped for improvement when the model is tested.



Pressure distributions on forebodies with
contours according to NACA 0014.2-N00.20

Figure 8: Pressure distribution on forebodies with contours according to NACA 0014.2-N00.20. Contour $n = 1$ chosen.

Note that the pressure minimum should occur at station 7000 on 2026. Recall that Schlichting [15] suggests transition occurs aft of the point of minimum pressure which lends support for the possible condition of laminar flow over the forward sensor up to station 4000.

The Swedish researchers conclude that the most significant design parameter is the pressure (velocity) distribution along the contour of the hull.

Finally, because of the increase in diameter of 2026 to 9.6 metres compared to Collins at 7.8 metres, it has been possible to extend the nose shape much further aft on 2026 using a series of conical sections aft of station 10000 which then join the cylindrical mid-section at station 16000.

The only detriment this may have on the design is a slight loss of headroom in the

forward quarters on the top deck. This would be a small price to pay for the advantage of an improved forward sonar but especially if laminar flow can be maintained over the nose to station 4000 at a speed of 10 knots.

If laminar flow cannot be achieved then the nose shape is equal to the best available as suggested by Gertler in his Figure 12 on p. 21, [10].

4.7 Construction Techniques

Past research in the area of maintaining natural laminar flow on aircraft surfaces as a means of drag reduction has concentrated on wing design. The results of this old research have been very successful in the design of lifting surfaces. Recently, Dobdele *et al* [23], investigated the design of laminar fuselages for business aircraft. Their work was motivated by the fact that fuselage drag contributes about 50% of the drag of an all turbulent transport and about 70% for a transport with laminar lifting surfaces.

Another motivation was the introduction of new construction techniques producing surfaces of such quality as to maintain natural laminar flow at high Reynolds numbers.

Waviness in the surface induces waviness in the contiguous streamlines which cause transition to turbulence.

Holmes *et al* [20], in their paper, describe the care with which such surfaces have to be produced and provide a method for measuring waviness. Holmes *et al* [22], (a different group of researchers) show the different types of surface faults to be avoided in manufacture whether the boundary layer is laminar or turbulent.

Having observed the high quality of construction of the interior of submarines it should be one hundred percent possible to build a portion of the external surface, 5 m of the nose, to the required standard for achieving laminar flow.

4.8 Factors Against Laminar Flow

Apart from construction defects like waviness or even more gross features like edges of shutters or worst of all, sharp changes in section with openings to the flow, the ever present problem preventing laminar flow is due to fouling. After weeks spent in tropical waters a submarine might return trailing a forest of growth especially if some time is spent not moving. Much effort is applied to this problem and there is no simple answer. With racing yachts continually exposed, one solution is to clean the surface on a regular basis.

Acoustic tiling is fitted to many submarines in order to reduce the reflected waves from an incident ping. By its very nature, there are many edges, each of which can act as a turbulence stimulator and produce added skin-friction drag. If fitted over the nose piece in the region of the forward sonar then there is no chance of establishing a laminar boundary layer there. The situation for the flow then becomes as described by Hess [13], with a fully turbulent boundary layer commencing at the nose.

However, it should be possible to cast a nose section of the required length including the acoustic tiling thus removing all edges and joins which would stimulate turbulence.

4.9 Boundary Layer Control

Apart from the possibilities of achieving the required length (4 m axial, 5.7 m peripheral) of natural laminar flow, there also exist various other techniques of boundary layer control which can prevent transition. The earlier report [1] mentions these. A recent paper sent to me by the principle author [24], discusses the progress with compliant coatings. This paper represents a joint international effort by the US Navy, the Russian Academy of Science and noted British researchers.

Again it is suggested that progress be kept under review for all forms of boundary layer control.

4.10 Symmetrical:Asymmetrical Nose shape

Many modern submarines carry a non-buoyant casing above the circular hull. The function of this casing is to cover hatch openings and to house certain equipment such as the winding gear and stowage drum for a towed array. It may also house certain sonar equipment as Admiral Hervey suggests [8]. He strongly disapproves of its use for stowage of odd items.

The shape of this casing causes an asymmetry in the hydrodynamic cross-section of the hull, consequently the pressure variation along a fore and aft line over the casing is different to that along a similar line of the circular cross-section.

At any particular cross-section this gives a pressure difference between a point on the casing compared to a point on the circular hull. Transverse pressure differences give rise to cross-flow and streamlines no longer flow symmetrically.

Over the nose it is desirable to have the flow as perfect as possible. Therefore it is desirable to commence the distortion due to the casing, aft of station 5000 and to make the distortion as gentle as possible with a prolonged lead into the final cross-section. Hence the shape of the nose as drawn.

Carmichael [11, p. 158], discusses flow problems which can be caused by asymmetry which produce transverse velocity components in the boundary layer and suggests they should be avoided. These asymmetrical velocities then produce vortices.

Unlike Collins but very like British submarines (and others) the casing cross-section is faired to the circular cross-section without a longitudinal valley which would promote vortices.

5 Aft Body Shape

The shape of the most aft sections on Collins caused no observable flow problems so the same cone angles and cone lengths have been adopted.

As the boat tail on 2026 needs to join to a larger diameter (9.6 m) than that of Collins (7.8 m), the intermediate cone sections are of different dimensions but similar in principle.

The shape which presented the most difficulty and carried the potential for causing the most serious flow problems was the aft end of the casing, the turtle back.

The design objective has been to produce a shape without any crossflows, which would create large vortices and associated velocity defects in the flow to the propeller. A model study should provide interesting information.

The principle followed in the shaping is to minimise any pressure differences at every cross-section, as with the nose entry to the casing.

6 Design of the Sail

The sail provides underwater handling stability, a bridge platform for conning the submarine on the surface and a supporting structure for about eight masts. It may also support the forward control fins.

In the past, the location of the sail has been dictated by through-hull penetration masts like periscopes which could only be located in certain positions. This should not apply in the future because of improved designs of such systems to provide non hull penetrating masts.

Choosing the correct height is important. If too tall it affects the centre of mass and may cause a greater snap roll as Admiral Hervey [8] suggests. Any non penetrating mast needs to be properly supported

Arentzen and Mandel [6] report that the drag of these large appendages may be between 15-30 % of the bare hull drag.

One large US SSN, Thresher, of 1956 vintage, had a problem reaching fleet speeds with the installed power. The sail was reduced to one quarter of its normal size in order to lower the drag but this meant the loss of important masts. Sail design has to be a compromise.

Hoerner [25], on p. 8.16, suggests that a large appendage like the sail suffers less interference drag when placed on the fore part of the main body, ahead of the maximum thickness. He also suggests (p. 8.10) it is an advantage to make the sail thin ($t/c \approx 8\%$). Because of their increased thickness near the base, sails on some submarines have suffered from flow separation. Thinner sails placed nearer to the nose help in this regard.

Captain Jackson in his paper on Submarine Parametrics [27], suggests a sail size of 26 feet high by 30 feet mean length for his design example. He then shows how the sail absorbs 30% of the effective horse power and more if it is larger.

The details of the position and shape of the sail will depend on the number of masts, type of power source, type of periscope as well as effects on steering and dynamic stability. These details should be considered after the testing of the model of the bare hull. As a tentative first move the sail is drawn moved forward by 2 m from its position on Collins in order to maintain the lateral stability and counter-balance the loss in lateral area aft.

7 Control Surfaces

It has been demonstrated on Albacore that ‘X’ arrangement of aft control surfaces gave a much tighter turning circle than with a conventional cruciform arrangement [26]. Heggstad [30] discusses the advantages of ‘X’ form rudders.

The aft control surfaces on Collins have operated successfully and there appears no reason to change this arrangement. Their proportions may need to be altered.

The forward control surfaces on Collins, mounted on the sail, high above the centre of mass with all their attendant control arrangements and heavy weights, detract from the stability margin.

British submarines favour forward placed hydroplanes on the hull (or casing). Russian submarines seem to favour mounting elsewhere to the sail (see [8, section 4]). The latest US submarine Seawolf has forward mounted hydroplanes ([28], p. 210 and 212) as does the British Swiftsure ([29] p. 86 and 87).

Forward positioned hydroplanes can apply greater control of depth with smaller forces because of their greater leverage, especially when moving slowly in shallow water at periscope depth. Their disadvantages are the need to retract when berthing and their water flow and control noise affecting signals to the forward passive sonar.

7.1 Stability and Control

The noted US naval architects and submarine designers, Arentzen and Mandel comment in their paper [6, pp 657-760], on stability and control, “A change in shape requires a complete new analysis of this subject early in the design but after the shape has been finalised including the sail, the control fins and the type of propulsor. This analysis is particularly important for motions in the vertical plane where the submarine should be able to operate at high speeds within a narrow vertical band, neither penetrating beyond its maximum operating depth which can lead to certain disaster nor breaching the surface of the water which could lead to disclosure at an inappropriate moment.”

Such analysis should occur at a later stage in the design process.

8 Profile of 2026

The profile of the proposed Submarine 2026 is shown in Figure 9. Also shown is the profile of Collins for comparison. The main change in the internal layout is the move aft of the torpedo tubes so a plan view shows this new arrangement. The most forward point of the shutters is aft of station 5000, giving the best opportunities for natural laminar flow over the forward sonar or the smoothest turbulent boundary layer with no added roughness.

The arrangement of four decks is also shown in cross section. It might be noted that for the lowest level - the bilge, although the maximum headroom is reduced compared to Collins, the contained volume is almost the same.

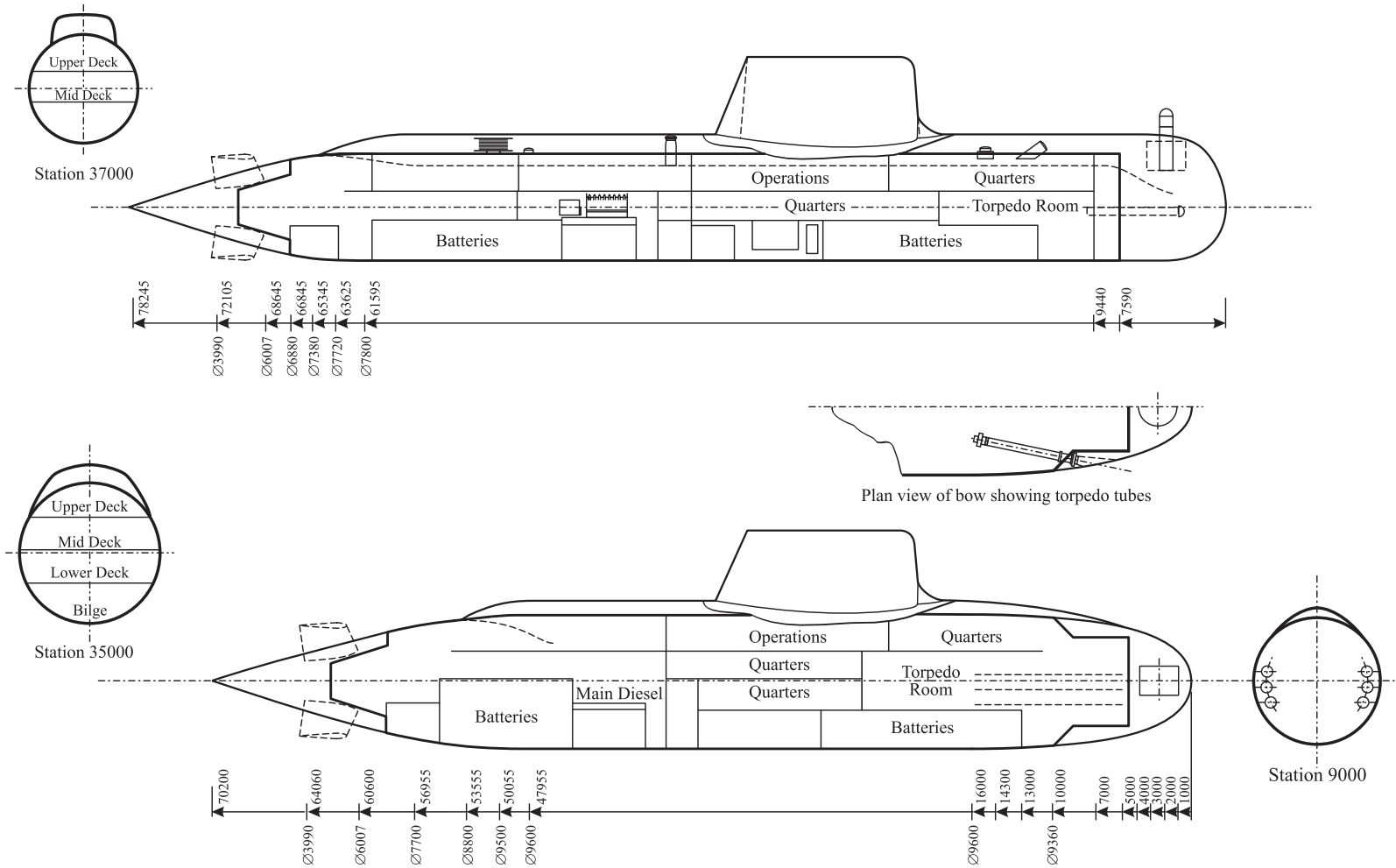


Figure 9: Profiles of 2026 and Collins.

9 Discussion

The reasons for design choices have been explained.

1. The maximum diameter has been increased from that of Collins (7.8 m) to 9.6 m for 2026.
2. This gives a more favourable L/D ratio of about 7.3 which should lower the total resistance coefficient. When combined with the reduction in prismatic coefficient from 0.85 to 0.76, the total drag coefficient should be reduced by over ten percent compared to Collins.
3. Because of the increased wetted surface in a longer, smaller diameter three level submarine, for equal volumes, the total resistance (and power) is over ten percent greater for the three level compared to the proposed four level submarine.
4. The increase in diameter should allow four decks in part of the vessel and give a more favourable ratio of deck area per unit volume as favoured by US submarine designers.
5. The length of the vessel could not be properly established and will depend on what is required to be accommodated. It was arbitrarily set at 70 metres which gives a greater submerged volume than Collins. The length can be adjusted in any final design by altering the length of the parallel mid-section.
6. The nose shape was drawn with a perfectly symmetrical shape up to station 5000, so that the flow in the region of the forward sonar could be as perfect as possible, either with a natural laminar boundary layer or with one which is turbulent but without any roughness.
7. The effect of the change in cross-section at the lead-in to the casing aft of station 5000 needs to be examined in the model tests to ensure minimum disruption to the boundary layer and to check the pressure distribution thereafter.
8. The nose shape chosen, for flow streamlines which do not continue over the casing, should give a falling pressure gradient up to station 16000. It is expected that the minimum pressure coefficient should not fall below $C_p = -0.27$, but this needs to be checked in the model experiment as the shape was extended beyond the analytical point of maximum cross-section.
9. Because of the desire to give the best possible conditions for reception by the forward sonar, it is suggested that the forward part of the nose up to station 10000 be constructed most carefully as a mathematically continuous surface to the finest tolerances of surface finish and waviness. Up to station 5000, there should be no disruptions to the surface over this forward part, no torpedo hatches, no obtrusive mine detectors, no holes, no torpedo discharge openings, just a smooth surface.
10. Part of this report is concerned with the possibilities of natural laminar flow occurring over the first portion of the nose up to station 4000. It does seem possible but is not proven. A definitive way to check this possibility would be to undertake some form of full scale testing.

11. Whether or not natural laminar flow can be established would be no reason to change the shape of the nose.
12. The design of the afterbody follows what has been proved as constructionally reasonable (successive conic sections) and has produced acceptable flow into the propeller.
13. The shape of the aft end of the casing (the turtle back) would be the most challenging aspect of the design. It was this feature which proved most troublesome on Collins. The proof of the proposed shape will be seen in the model tests.
14. Apart from the hull shape, important items like the sail and control surfaces have not been drawn. These need to be optimised for position, size and shape to maximise operational effectiveness and minimise resistance.
15. After the model has been tested and drag coefficients determined, the speed-power relationship can be estimated following the guidelines of Captain Jackson [26].

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Appendix A Circularity

Captain H. E. Saunders, a famous US Naval Architect, in the discussion to the paper by A. I. McKee [4, p 643],

“With external pressures as high as they are on the modern submarine, and with a factor of safety that has always been lower than that of almost any other mad-made structure, making the pressure-proof shell and its stiffening frames truly circular is extremely important. In fact, the easiest, cheapest, and most efficient means of increasing the working depth, or the factor of safety, with no increase in weight, is to make the heavy hull sections *exactly* circular. This situation is dictated by science and logic, and should not be upset by arguments of the production personnel. If we really possess the ingenuity with which we like to credit to ourselves, we can certainly find ways to prove that the tolerances we need on circularity are genuinely microscopic.”

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19. ABSTRACT A shape for a next generation submarine has been drawn based on a survey of available knowledge. The reasons for each detailed portion of the shape are explained. The aim of the design is to produce a submarine with minimum practical resistance and with minimum water flow noise especially over the forward passive sonar while still carrying out all its normal functions. It is assumed the role of the submarine would be little different from the current vessel but may be powered differently and carry different equipment. The diameter of the hull has been increased while the length has been decreased compared to the present vessel. It is estimated the comparative resistance will be reduced by ten percent. The larger diameter will allow an extra deck over a portion of the length of the vessel giving greater flexibility to internal arrangements. All openings in the first five metres of the shape have been moved elsewhere including the torpedo tubes and interceptor array, to give the smoothest possible flow over the forward passive sensors. The nose shape is derived from a NACA forebody with a 14.2 percent thickness-length ratio and shows a favourable value of the minimum pressure over its length. The question of achieving natural laminar flow over this short length is discussed and found to be possible but is unproven.					